Printing Space: Using 3D Printing of Digital Terrain Models in Geosciences Education and Research

Seth S. Horowitz[1,a] and Peter H. Schultz[2]

ABSTRACT

Data visualization is a core component of every scientific project; however, generation of physical models previously depended on expensive or labor-intensive molding, sculpting, or laser sintering techniques. Physical models have the advantage of providing not only visual but also tactile modes of inspection, thereby allowing easier visual inspection as well as access to the visually challenged. Recent advances in three-dimensional (3D) printing technology have created low-cost systems capable of translating 3D shape and terrain elevation models into physical models. Low-cost, commercially available, 3D printers are capable of using data from topographical maps, radar data, altimetry, and digital terrain models and turning them into accurate, handleable, 3D models out of multiple materials within hours. The resultant models not only provide study materials for lunar and planetary terrains and small space bodies but also allow the generation of libraries of physical objects accessible to the visually impaired. Moreover, these models create new tools for introducing space sciences to the roster of accessible science curricular materials. © *2014 National Association of Geoscience Teachers*. [DOI: 10.5408/13-031.1]

Key words: geology, education, relief maps, 3D printing, asteroids, terrain, craters, visually impaired

INTRODUCTION

Learning is enhanced by the use of materials that engage more than one sensory modality. Three-dimensional (3D) terrain modeling has been a useful tool for cartography and geology since the first relief globes of Earth made in 1752 (Destombes, 1978). Custom-made relief globes of the Moon based on early telescopic and orbiter data were used extensively for planning the Apollo Moon landings (Fig. 1). Stereo imaging from spacecraft can be based on either paired cameras on landers and rovers or on integration of displacement images from orbiters. Consequently, 3D image reconstructions have become a common tool for terrain modeling.

Although advances in imaging and video technology have yielded exceptional surface reconstruction capability, the technology is restricted to visual interpretation. Such a restriction limits both its research and educational use. First, many 3D visualizations are limited by the field of view of the original image capture and provide only limited degrees of enhancement. Second, anaglyphic (two-color stereoscopic), polarization difference, and digital 3D imaging is restricted to those with full stereo vision only. The ability to provide 3D physical models based on digital elevation terrain and other reflective data sets, such as gravity data or radar, can provide enhanced intuitive grasp of data sets for the public. Models open entirely new fields to the visually challenged, not only from holding objects for the blind but also from perspective changes for persons with only monocular vision.

Tactile maps for the visually disabled have been in use since the mid-19th century (Briesemeister, 1957). Currently, a variety of tactile maps are made to aid the blind in learning about geography and to help with navigation in a sighted world (Available at: http://www.terrainmodels.com/tactile.html; accessed 23 November 2013). In addition, relief maps have a long and storied history in surveying, military, and exploratory endeavors to increase the efficacy of long-distance mission planning (Baldock, 1967; Turner and Sherman, 1986; Stempien, 2002). Relief-type maps have traditionally been constructed from physically carved models. More recently, thermoplastic vacuum molding has been used to create textured sheets from the original models. With the advent of low-cost, 3D, prototyping devices, however, it is now possible to create customized, 3D elevation maps and models of items ranging from biological structures, derived from computed tomography (CT) scans to asteroids to planetary landscapes. Because teaching accessible science is a major thrust of many schools, not only for the visually impaired but for all students, the ability to create tactile models of both terrestrial and extraterrestrial surfaces will allow educators and scientists to expand their repertoire of teaching materials for physical sciences.

MATERIALS AND METHODS

Data Sources

3D models can be derived from a variety of sources and formats. Terrestrial, lunar, and Martian terrain data, based on optical and laser altimetry data as well as radar data from space and ground sources, can be translated into 3D data sets, which can be transformed into printable formats.

Data sources include archived images and data sets from planetary data centers as well as numerous online sources (e.g., http://hirise.lpl.arizona.edu/dtm/, accessed 23 November 2013; http://echo.jpl.nasa.gov/links.html, accessed 23 November 2013). Selection of the data source depends on the type of model to be created. For reconstruction of surface features, such as craters or valleys, two-dimensional (2D), color-coded, altimetry images with at least eight levels of contrast are sufficient for modest-sized models, with more extensive color or grayscale gradations for resolution of

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[1]The Engine Institute, Warwick, Rhode Island 02888, USA
[2]Department of Geological Sciences, Brown University, 324 Brook Street, Providence, Rhode Island 02912, USA
[a]Author to whom correspondence should be addressed. Electronic mail: shorowitz@neuropop.com

FIGURE 1: Relief map of the Mare Nectaris region of the Moon, constructed by the Army Map Service in 1961 based on telescopic observations. Similar (but much higher resolution) base-relief maps were later constructed from each Apollo landing site.

finer-scale models. For creation of globes (i.e., largely regular bodies, such as planets or differentiated moons), cylindrical projections of altimetry data can be transformed and remapped onto spheres with variable altitude scaling. This strategy allows the generation of globes with greater vertical exaggeration to enhance the tactile feedback and identification of features. Although it is possible to generate both planar surface features and globes from optical data (shadowed surfaces), in general, such models suffer from significant elevation artifacts because of differences in illumination angles, which limit their utility.

The creation of models of irregularly shaped, non-differentiated space bodies, such as asteroids, require digital elevation data sets, e.g., radar, altimetry, and optically generated shape models. Such data sets come in a variety of formats: from three-axis (x, y, z) distance data referenced to a central point (allowing creation of a point cloud shape) to preformatted 3D shapes, often presented as wavefront (.obj), Autodesk Max (.3ds; Autodesk, Inc., San Rafael, CA), or stereolithography (.stl) formats, which are amenable to 3D printing. Additionally, it is possible, although more difficult, to generate shape models from raw, orbital, altimetry images using online 3D point cloud integration and generation tools. These models, however, tend to be substantially lower resolution than other available sources and are best used when no other sources are available or as an exercise in data convolution.

Software

Conversion from images or raw data to 3D models can be carried out with a variety of modeling software, including commercial packages, such as Rhino3D (Robert McNeel & Associates, Seattle, WA), or 3D Studio Max or Maya (Autodesk). Several free, open-source software environments, such as Blender (available at: http://www.blender.org, accessed 23 November 2013; Blender Foundation, Amsterdam, the Netherlands), MeshLab (3D-CoForm Project, Brighton, UK), or even ImageJ (National Institutes of Health, Bethesda, MD) are also capable of creating and editing 3D models to create printable stereolithography models. Each program has its own strengths and peculiarities and will require varying degrees of familiarity by the user to achieve printable models. Examples given below will be based on work using Rhino3D, unless otherwise indicated; however, all these (and other) software packages are capable of carrying out the same core actions.

Following the generation of the .stl model, printer-specific programs prepare the model for translation into a physical model. Consumer-available, fused-deposition printers use melted plastic as the substrate (because this will be of the most utility for those on limited budgets) using programs that are typically open source (and frequently updated), such as ReplicatorG (available at: http://replicat.org, accessed 23 November 2013). Such programs carry out automatic error checking and print optimization with relatively user-friendly interfaces, thereby allowing basic modifications to the model, such as scaling, rotation, variable print density, and previewing the final model configuration. Users with code experience in Python programming language are able to carry out modifications to these programs.

3D Printers

3D printers have been around in various iterations for several decades. Today, many commercially available services will print 3D models in a variety of materials, including plastic, glass, ceramic, and metal, and allow the end user to avoid the complications of managing their own printing. Such services allow the use of specialized materials or the generation of large and very fine-grained models for high-quality products. Although valuable for museums and quality models, that approach can be expensive. Moreover, the interim between submitting the model and receiving the final version can be a month or more.

Inexpensive, consumer-based, 3D printers have only been available commercially since about 2009 with the introduction of the RepRap (available at: http://reprap.org; accessed 23 November 2013) and, shortly thereafter, the Makerbot Cupcake CNC (MakerBot Industries, Brooklyn, NY). These early units had limited build areas (approximately 10 × 10 × 15 cm height) and were restricted to relatively coarse (1 mm vertical resolution) printing with acrylonitrile butadiene styrene (ABS) plastic. Since then, there have been many modifications and upgrades to user-based 3D printers with increased resolutions, build volumes, and flexibility in printing materials. Although there are now about a dozen desktop, consumer-based, 3D printers available, each with it's own specifications and limitations, examples below will be based on the current version of the Makerbot Replicator, a third-generation, fused-deposition model (FDM) printer of modest cost with a 23 × 15 × 15 cm high build envelope with 0.2–0.3 mm layer thickness capable of printing in ABS and polylactic acid (PLA), a corn-based, nonfuming plastic, as well as several other materials. The advantage of this unit, aside from its open–source architecture, is its relative portability, simplicity of operation and maintenance, and ability to print from a memory card, thus releasing the end user from having it tethered to a computer.

Although 3D modeling and printing is not automated and requires some supervision, it is relatively straightforward to operate. In addition, because the printers require little external resources while operating, a 3D printing setup can run independently from a desktop computer, laptop, or netbook. This portability permits transporting the printer to different sites for demonstrations or temporary classrooms and exhibits. Both ABS and PLA filament-based models are nontoxic, sturdy, water resistant, and lightweight enough to be easily transported. Furthermore, the material cost is low enough to generate and distribute many models at low cost.

Sample Printing Materials and Procedures

This section covers the basic techniques for creation of printable 3D models of surface features, variable exaggeration globes, and irregular space bodies. The models are based on publically available data sets, use of Corel Photo (Corel Inc., Menlo Park, CA), Rhino3D, Meshlab, and ReplicatorG software, and printing parameters based on a Makerbot Replicator desktop printer. Although each software and printer package has its own specific commands and parameters, those presented below illustrate the capability of easy adaptation to other systems.

Printing Gale Crater on Mars From Altimetry Data

Gale Crater is a 154-km-wide, 3.5–3.8-billion-y-old crater located in the Aeolius region of Mars (http://planetarynames.wr.usgs.gov/Feature/2071; accessed 23 November 2013) and is the landing site of the National Aeronautics and Space Administration (NASA) rover Curiosity in 2012. The site is of geological interest because of the presence of layered sequences (potentially recording changes in climate) and a diverse landscape, including evidence for flow of water (channels with depositional features at their termini). A 3D print of this crater offers substantially more information about its complex conformations than is available solely from visual analysis of planar altimetry images. Initial data were derived from Mars Orbiter Laser Altimetry (MOLA) data set, presented as a 2D image with color-coded height [https://en.wikipedia.org/wiki/File:Topographic_Map_of_Gale_Crater.jpg, accessed 23 November 2013]. The image was modified by removing the landing ellipse and converting the colors to grayscale to indicate depth using Corel PhotoPaint (Corel), with deeper elevations converted to darker grays. This strategy serves to illustrate the use of easily accessed images. The corrected image was then imported into Rhino3D v 4.0 and converted into a vertical displacement model using the heightfield command [Fig. 2(B)]. Heightfield is a 3D modeling command that assigns a gray shade or color value of a planar bitmap image into elevation levels, i.e., black is the base with white forming the highest peaks. The model was then converted to a mesh with outlines formed from mesh edges and extended downward vertically to create a shallow box to provide a flat base. This was then combined with the generated heightfield using the mesh "Boolean union" command, which integrates separate pieces of the model into single mesh elements to create a printable slab. This was then exported from Rhino3D as a stereolithography (.stl) file and opened in MeshLab. The file was then altered using the Quadric Edge Collapse Decimation filter under the Remeshing, Simplification, and Reconstruction submenu to eliminate excessively sharp features that can generate printing artifacts. The model was then resaved as an .stl file and opened in ReplicatorG for preprint processing, including centering and rescaling to fit on the build platform, slicing with a 0.27-mm layer height, one outline shell selected to provide additional strength to fine features during printing, and 10% infill density, providing a lightweight but strong print that uses relatively minimal plastic. Upon completion of the ReplicatorG slicing, the model was saved as a G code, the native software for driving the Replicator (and other 3D printers) and printed using gray ABS plastic, requiring about 1.5 h to print a 4-in. by 4-in. model [Fig. 2(C)].

Printing Mars Globes With Variable, Vertical Exaggeration

Tactile globes of planets and moons are not only useful for the visually impaired but for sighted individuals as well. Almost all visual and tactile models use vertical exaggeration to illustrate the relative extent and shape of geological features. Mars is a particularly useful example, given the extreme heights of its major volcanic edifices (e.g., Olympus Mons) and depths of its valleys (e.g., Valles Marineris). Attempts to create models with no vertical exaggeration will leave the end user with an almost spherical shape, even at the finest levels of resolution. This illustrates the limits on topography from gravity and surface processes on large bodies. The Mars globes presented here use the same basic data sources, but vary the relative vertical dimension using only a single command in Rhino3D. A grayscale, cylindrical projection of MOLA data of the entire Martian surface [Fig. 3(A); http://www.buining.com/planets/MarsDEM2880.png, accessed 23 November 2013] was imported into Rhino3D, scaled to fit the build platform, and then converted into a heightfield and a mesh as above. A sphere was then generated using the Solid command with a radius equal to the width of the heightfield/2π and aligned underneath the center of the heightfield. The heightfield was then applied to the sphere using the Mesh command ApplyMeshUVN [Figs. 3(B) and 3(C)]. A vertical height setting (V option) of 1.0 yields a globe with a vertical exaggeration of approximately ×50 [Fig. 3(D)], while using a setting of 0.2 yields a vertical exaggeration of approximately ×10 [Fig. 3(E)]. The model was then saved as an .stl file and passed to ReplicatorG, using the same printer settings as for Gale crater. Raft (which stabilizes the print on the platform) and exterior support (which position thin, plastic sheets under printable elements with more than 60° overhang) were selected to prevent filament droop, which can yield a "drippy" model in the lower region. Although it is possible to create completely hollow globes (using a 0% infill setting), that strategy requires the use of an additional shell and often results in relatively fragile models, particularly at the top and bottom. These two globes provide different resources for the users; the highly exaggerated globe provides clear, tactile features, allowing a user to identify major geological landmarks and

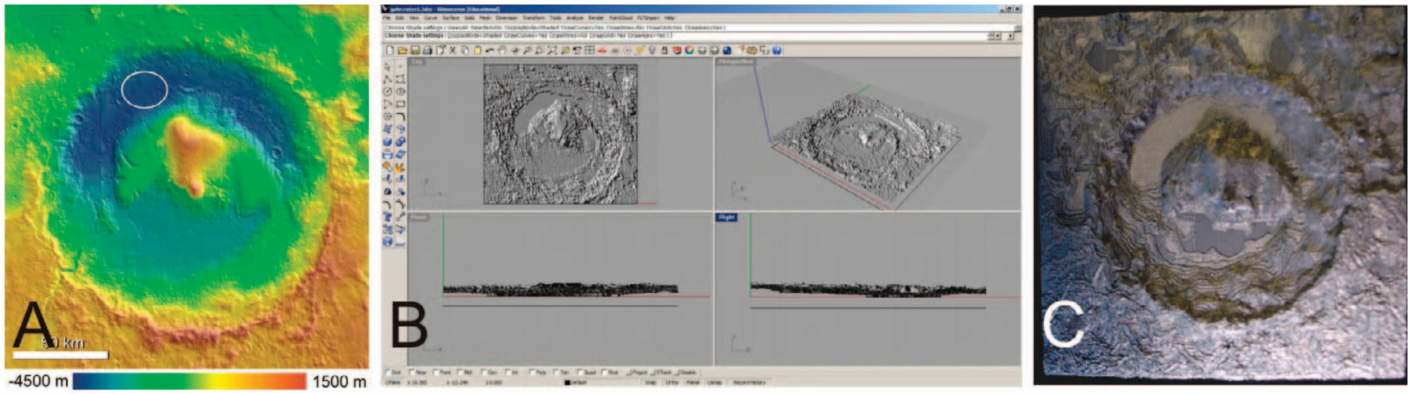

FIGURE 2: Creating a 3D print of the Gale Crater on Mars. (A) Color-coded topographical image from MOLA data. (B) Heightfield generated in Rhino3D, based on depth information in Fig 2(A). (C) 3D printed model in gray ABS plastic.

relative position by touch alone, whereas the less-exaggerated version can easily be painted (or not) and used as a display model.

Printing Asteroid 4179, Toutatis, and Other Irregular, Small Space Bodies

A variety of shape models, in Wavefront (.obj) format, for small planetary bodies are freely available through the Jet Propulsion Laboratory (JPL) asteroid and radar link page (http://echo.jpl.nasa.gov/links.html; accessed 23 November 2013). Use of those shape models saves significant time in model development because they can be easily converted to .stl files. Because long-distance radar provides relatively coarse measurements, adequate shape models can be created from the data but rarely at high enough resolution to show accurate surface texture. Asteroids 4179 Toutatis is an irregularly shaped, Apollo Mars–crossing asteroid that is $4.5 \times 2.4 \times 1.9$ km in dimension and is an excellent example for printing a nondifferentiated body. The .obj file from the JPL archive page was downloaded and imported into Rhino3D, rotated so that it lay relatively flat on the x–y plane, rescaled to fill the build platform [Fig. 4(A)], and exported as an .stl file. The .stl file was opened in ReplicatorG and printed using the same parameters as above, including a raft and exterior support to prevent overhangs [Fig. 4(B)]. Using similar resources and procedures, other small space bodies can be printed and scaled to create collections showing relative size of the actual bodies or be varied in size to show similar relative degree of detail [Fig. 4(C)].

RESULTS AND DISCUSSION

The expanded availability of open-access space and terrestrial data sets, combined with the emergence of low-cost, user-friendly 3D printers, creates an opportunity to make high-quality, handleable, physical models for educational and research purposes. These models can significantly increase the quantity and quality of accessible science materials for visually challenged students, teachers, and researchers, an underrepresented population for whom providing curricular materials is often a challenge (Travis, 1990; Asher, 2001). Previous methodologies have included the use of traditional, tactile globes and maps (Caldwell, 2001); clay models based on digital elevation data (Permenter and Runyon, 2003); voice to text, tactile models; data sonification (Ceylan, 2011); and EMBed (e.g., maps and body) techniques (Howe, 2006). Although these methodologies provided important resources for teaching physical sciences to the visually impaired, they each imposed significant constraints on the translated information, as well as substantial reliance on external manpower (or cost) to create, provide, and explain the tools.

Although the use of 3D modeling software and printers requires some expertise and is not amenable to use by the visually impaired directly, the ability to develop a large and standardized library of materials, ranging from terrestrial terrain features to asteroids and globes, can allow a single 3D ''librarian'' to generate curricular and research materials for a significant population of students and users. Computer-savvy students can not only learn but modify both the data sets and the programs using extensive online resources, available free through clubs, university/college partnerships, or mentors. In addition, because many of the existing printers use open-source hardware as well as software, they can gain expertise in programming and robotics while tailoring their systems for their particular purposes.

The utility of 3D printed models by the sighted should not be underestimated. Three-dimensional printing can be used to introduce students to basic concepts, such as generating physical representations of mathematical forms, including platonic solids or formulae, such as three-axis, quadratic surfaces. In addition, the model can engage students in translating worlds into different coordinate systems (Cartesian, polar, etc.) and introducing (or enhancing) computational methods. In this sense, the construction of the models becomes an end in itself.

The most basic advantage of using 3D printed models lies in their ability to engage multiple senses. Although the state of knowledge about tactile object detection and identification is limited, compared with other modalities, human tool-using ability is based on our ability to integrate both fine vision and precision manipulation of objects. Tactile sensory events are processed in the brain via parallel networks to those of vision and audition (Harrar and Harris,

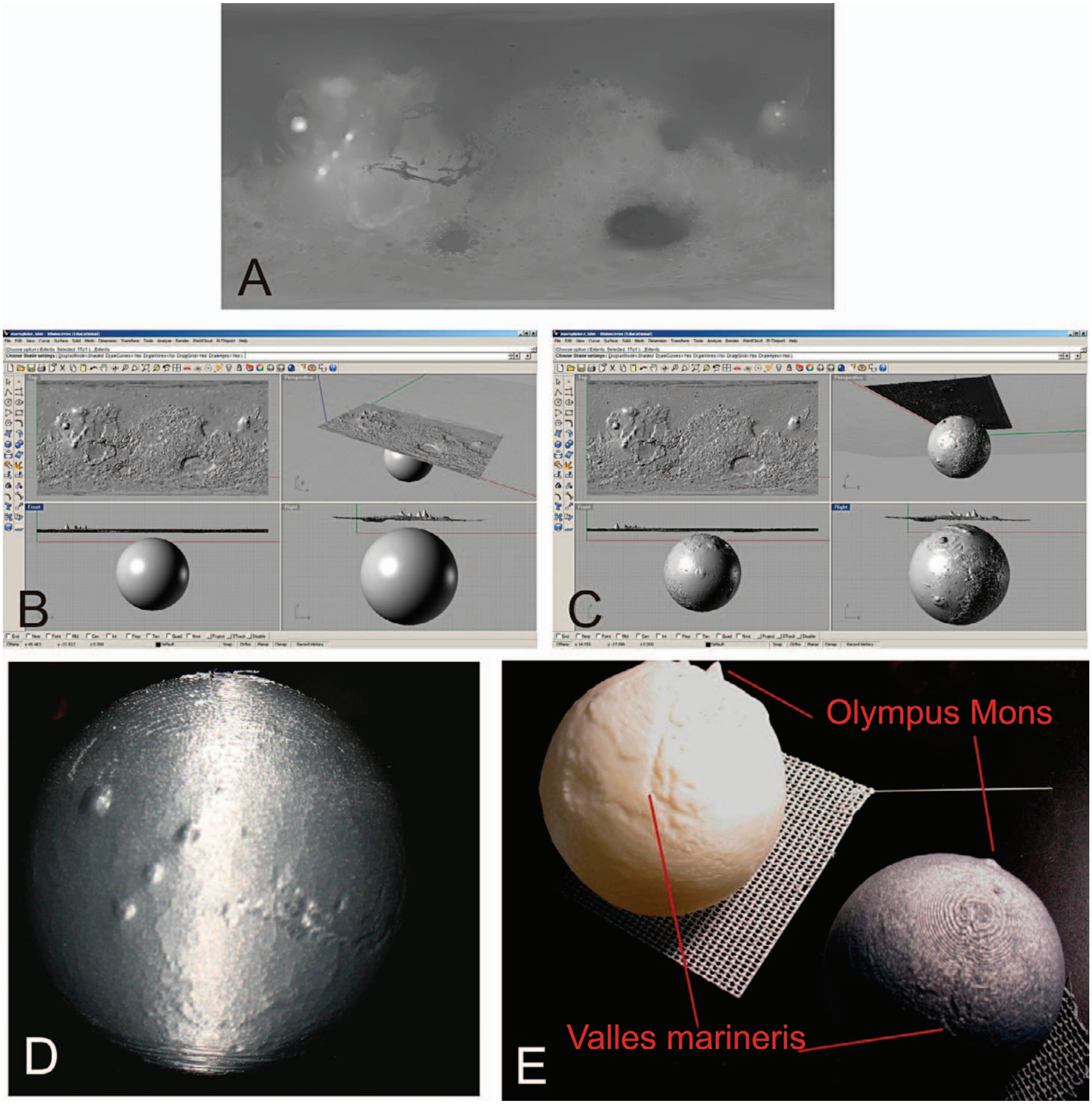

FIGURE 3: Creating 3D printed globes of Mars with different scales of vertical exaggeration. (A) Grayscale, cylindrical projection of Martian surface from MOLA data. (B) Planar heightfield generated in Rhino3D, based on depth information in Fig. 3(A), aligned with sphere primitive (below). (C) ApplyMeshUVN command with vertical setting of 1.0 to create an approximately 50-times, exaggerated, vertical conformation, mapped onto sphere. (D) 3D-printed Mars globe in gray ABS with 10 times the vertical exaggeration. (E) Comparison of ABS printed Mars globes on print-stabilizing rafts comparing high (left) and low (right) vertical exaggeration with major features Olympus Mons and Valles Marineris identified for comparison of elevated and depressed features.

2005) and likely are brought into common registration in the superior colliculus of the midbrain (Sparks and Nelson, 1987) to help create the perception of a multimodal object. Repeated exposure to shapes by touch has been shown to decrease errors in shape categorization and recognition and greater discriminability of shapes (Gaiert et al., 2012). Our tactile sensations and perceptions generate a “tactile consciousness” which is integrated into our overall spatial

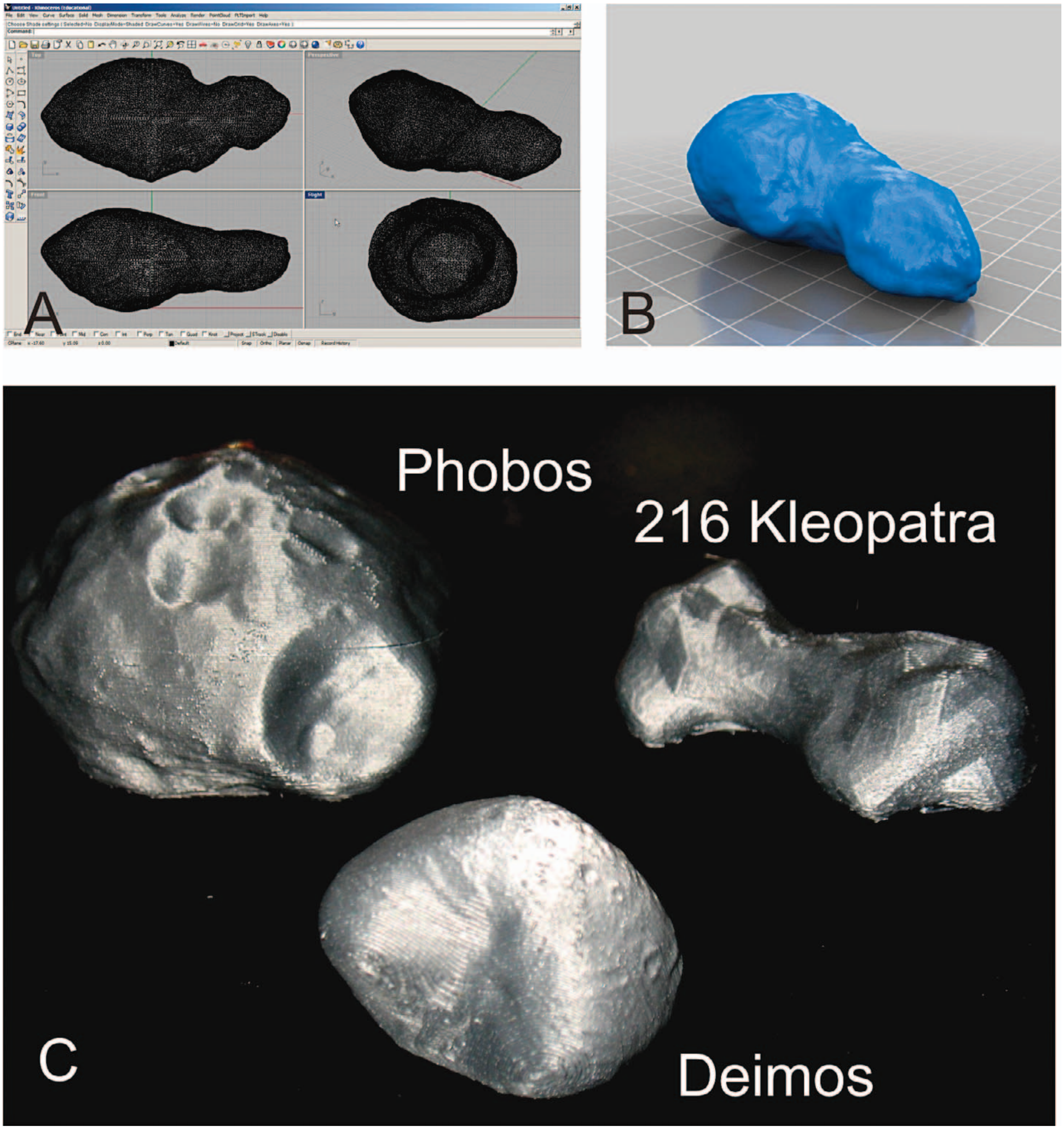

FIGURE 4: Creating 3D prints of small, irregular space bodies. (A) Wavefront .obj file of asteroid 4179, Toutatis, based on radar data imported from the JPL archive. (B) Printable .stl model of Toutatis. (C) 3D-printed models of Martian moons Phobos and Deimos and the main belt asteroid 216, Kleopatra, printed in gray ABS plastic (models not to scale).

intelligence (Gallace and Spence, 2008). Beyond the basic neural substrates that integrate touch and vision, the simple ability to rotate a physical object can often bring new elements into view for evaluation that would not be detectable using digital models alone (Horowitz, 2012).

To illustrate this point, one of the coauthors (P.H.S.) recreated the nearside surface of the Moon as a 6th grader, using modeling clay and observations with a 4-in. reflecting telescope (Fig. 5). The result looked remarkably like the Nasmyth and Carpenter (1874) efforts of 80 years earlier

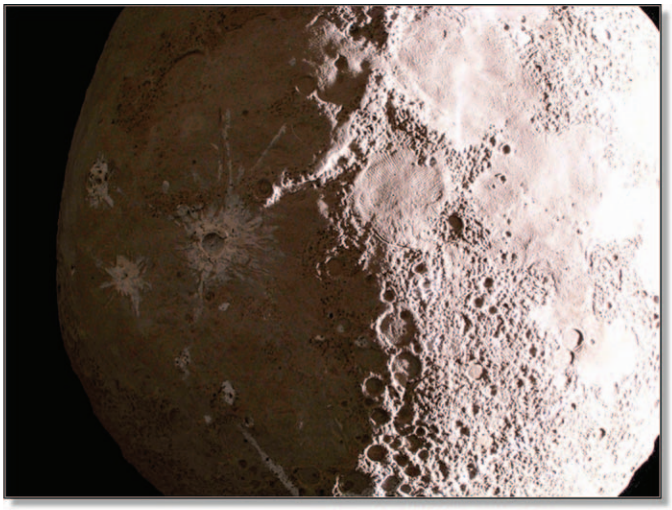

FIGURE 5. Clay model of the Moon based on telescopic observations, constructed as a science project by one of the authors (P.H.S.). The process of constructing that model led to questions about processes that result in simple (bowl shaped) versus complex (flat floored) craters.

(Fig. 6). That exercise helped to focus on the distinction between simple craters (using the ends of finishing nails) and complex craters (using flat-head nails). The process of creating a tactile model internalized the underlying processes that shaped the Moon, which evolved into a career in planetary science. 3D printing represents an alternative to that personal experience.

The 3D printing of scientific models is not limited to large-scale objects or long-range data sets from planetary science. The ability to scale models enables researchers to use x-ray micro-CT image sets to create 3D printable models for radiolarian and foraminifera and to create enlarged models of those organisms to teach the blind (Teshima et al., 2010). In addition, by appropriate filtering of CT data sets, inclusions of biological samples in fossilized amber or geological matrices can be extracted (Knecht et al., 2012) and converted into 3D printed models, allowing researchers the opportunity to handle samples otherwise restricted to visual manipulation. These can again be integrated into libraries of biological and paleontological samples to be made available on demand by other researchers and students, with the benefits of having a physical model, and without the possibility of damage to the original sample. In addition, models that require large-scale, high-resolution, or high-durability or specialized materials, such as ceramic, metal, or glass, can be outsourced, with the locally printed models acting as error-checking prototypes.

We suggest that data centers and research departments in the physical, biological, and mathematical sciences embrace the use of 3D printing technology to create archival and on-demand, physical model libraries for distribution to students and researchers. Such libraries could be generated from submitted data files and be made available via open-access protocols on Web sites, similar to those in the 3D printing hobbyist communities (e.g., http://www.thingiverse.com; accessed 23 November 2013) and printed in locations for local use or for distribution to schools for the blind and educational outreach centers, such as museums and planetaria, as well as retained for local use in teaching and research. although the cost and quality of such systems will inevitably become better, the technology has reached a point where its adoption can provide critical pedagogical elements to both underrepresented populations and the science community.

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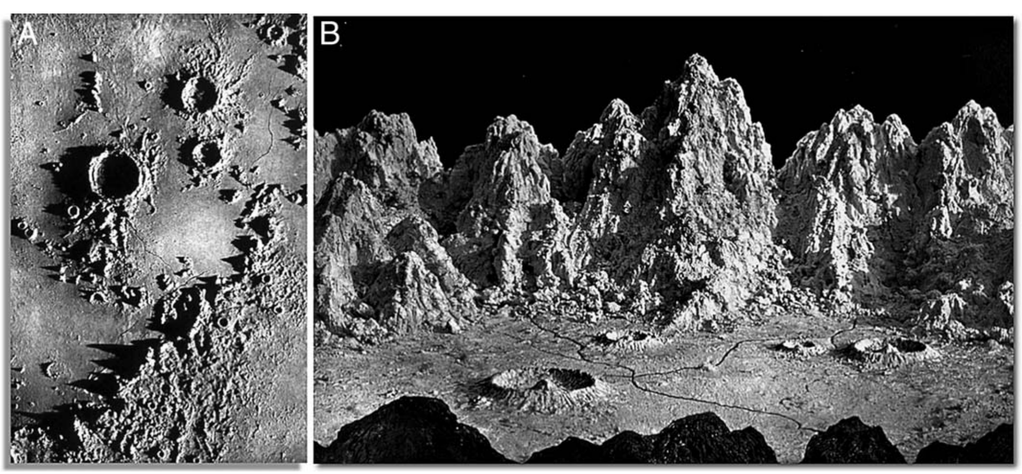

FIGURE 6. Plaster model of the Moon created from telescopic observations (Nasmyth and Carpenter, 1874). These models were photographed with grazing illumination to illustrate the lunar landscape. (A) A view of the Apennine Mountains, which forms part of the Imbrium Basin. Apollo 15 landed at the base of these mountains (lower left center). (B) The same region as in Fig. 6(A) but viewed from the surface. This image was created from sculpted plaster of paris. Such exaggerated views both stimulated the public (and scientific) perceptions of the lunar landscape. Now, high-resolution 3D printers can recreate accurate perspectives, whether above [Fig. 6(A)] or on the surface [Fig. 6(B)], and stimulate the imagination of future explorers.

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